II. SAFIR – Key Objectives

Background

The Single Aperture Far Infrared (SAFIR) telescope facility is proposed as the next infrared great observatory, following the Spitzer Space Telescope (SST), the James Webb Space Telescope (JWST), as well as the Stratospheric Observatory for Infrared Astronomy (SOFIA) and Herschel, and building on their science. This telescope would target the critical far infrared and submillimeter spectrum between that covered by JWST and that accessible routinely from the ground, at sensitivity levels orders of magnitude higher than SST, Herschel, and SOFIA, and with spatial resolution far higher than that anything yet achieved in the far infrared. The far infrared part of the spectrum is the key to understanding the formation of stars and planets, and the development of prebiotic chemistry. It probes the spectral peaks of the earliest galaxies, star formation and chemical enrichment history of galaxies, offers clues to the structure and habitability of nearby solar systems, and provides spectral tracers of the chemistry of life in such solar systems that are now forming. This part of the spectrum is inaccessible from the surface of the Earth, because of atmospheric opacity, but is available in its entirety from space. Due to zodiacal emission and scattering at short wavelengths, and the cosmic microwave background radiation at long wavelengths, it provides the darkest skies accessible for pathbreaking research on the stellar and gaseous components of the universe. Of special significance to SAFIR is the dramatic technological improvements, both in sensitivity and format, that have been made in infrared sensors. The trajectory of these improvements point to fully background limited performance for both imaging and low- to moderate resolution spectroscopy in arrays that can fill a telescope focal plane. As such, SAFIR represents critical scientific need that addresses strategic science goals of the agency, met by new technology for detectors and telescope architecture that offers a clear path to achieve those scientific goals.

The scientific importance of such a telescope has been codified in the 2000 Decadal Report of the National Research Council ("Astronomy and Astrophysics in the New Millenium", National Academy Press 2001), where it appears on an investment priority list of missions to begin development in this decade. This priority is reflected in successive endorsements from strategic planning exercises within the agency.

Technologically, SAFIR not only capitalizes strongly on the heritage from earlier missions, but also clearly points the way to much more ambitious missions. A notional mission plan for far infrared and submillimeter astrophysics has been developed by the community – "Community Plan for Far-IR/Sub-mm Space Astronomy"[1] and is reflected in Vision Mission and Origins Probe studies now being delivered to the agency. In the longest term, we are aware and cautiously optimistic about the potential value of the President's Exploration Initiative to space astronomy. We have developed a baseline SAFIR as a fully autonomous mission that is, as JWST, a single-mission observatory. Yet the steep trajectory of focal plane instrument sophistication and capability, the lessons and benefits accrued from Hubble Space Telescope servicing, and the new human and robotic opportunities that could become available from the Exploration Initiative suggest that opportunities for *servicing* SAFIR could bring science value to the mission that is otherwise unachievable. Efforts to map out such an opportunity are ongoing, and are broadly summarized in this report (see Section XIV). The development of such opportunity is, by enabling science that could otherwise not be performed, very much in the interest of the science community.

[1] *in New Concepts for Far-Infrared and Submillimeter Space Astronomy, D. Benford & D. Leisawitz, eds. (Washington, DC: NASA), NASA CP-2003-212233 --* http://safir.jpl.nasa.gov/documents/Community_Plan_printed.pdf

Notional Mission Assumptions

While the detailed requirements for SAFIR are driven by the key science objectives that it would perform, these requirements are bounded by practicalities, economies, and natural limits. We thus begin with the notional mission for SAFIR as a 10 m-class filled aperture telescope operating in a diffraction-limited ($1.22\lambda/D=0.5''$ at 20 μm) mode between the JWST long wavelength limit and the ground-based submillimeter short wavelength limit, and photon limited on the celestial background at all wavelengths. The size of the telescope is chosen as one that can fit in an EELV using at least some JWST architecture heritage (see Section VI). The background-limited goal for SAFIR is a strong driver on the operating telescope temperature. The telescope would be equipped with diffraction-limited wide field direct detection imagers, low-moderate resolution ($R\sim10^{2-3}$) direct detection spectrometers, and high resolution ($R\sim10^{6}$) heterodyne spectrometers.

Key Science Objectives

Within these notional guidelines, the key science objectives for SAFIR may be stated.

- Probe the earliest epochs of metal enrichment and see the galaxy-forming universe before metals. Understand the origin of dust grains in the universe.

- Resolve the far infrared cosmic background - trace formation and evolution of starforming and active galaxies since the dawn of the universe, and measure the history of star formation.

- Explore the connection between embedded nuclear black holes and their host galaxies. Understand the relationship of active nuclei to galaxy formation.

- Track the chemistry of life. Follow prebiotic molecules, ices, and minerals from clouds to nascent solar systems.

- Identify young solar systems from debris disk structure and map the birth of planetary systems from deep within obscuring envelopes. Assess the degree of bombardment they face, and the degree of habitability.

These key science objectives are developed in detail in Section III below. In order to do this credibly, we provide a careful assessment of the performance goals for the notional SAFIR.

Background-limited performance of SAFIR

In this section, we develop the capabilities of the notional mission assumptions listed above. While the anticipated background-limited sensitivity of SAFIR is discussed in detail in Appendix B it is useful to review, at this point, our understanding of the cosmic background radiation, which establishes the sensitivity floor that any mission could achieve. Our understanding of these backgrounds is due in large measure to COBE and ISO, and is being confirmed in detail with measurements from Spitzer. Figure II-1 below shows the three natural components of the uniform cosmic background over the range of wavelengths in which the notional SAFIR would operate. The strongest source of background at short wavelengths is zodiacal emission and galactic background emission. The data plotted are for the Lockman Hole, for which the galactic background is minimum and (since it is at an ecliptic latitude of 44°) the zodiacal emission is also fairly low. The SPOT extragalactic background is the mean background as established for Spitzer planning using extrapolated ISO source statistics, and the CMB is represented by a 2.7° blackbody. The total background is also shown, as is the BLIP sensitivity that would be realized if these were the only noise sources. It is clear from this plot that the universe is remarkably dark in the far infrared, and SAFIR can be the first observatory to take full advantage of that. It is this low background that drives the design temperature of SAFIR.

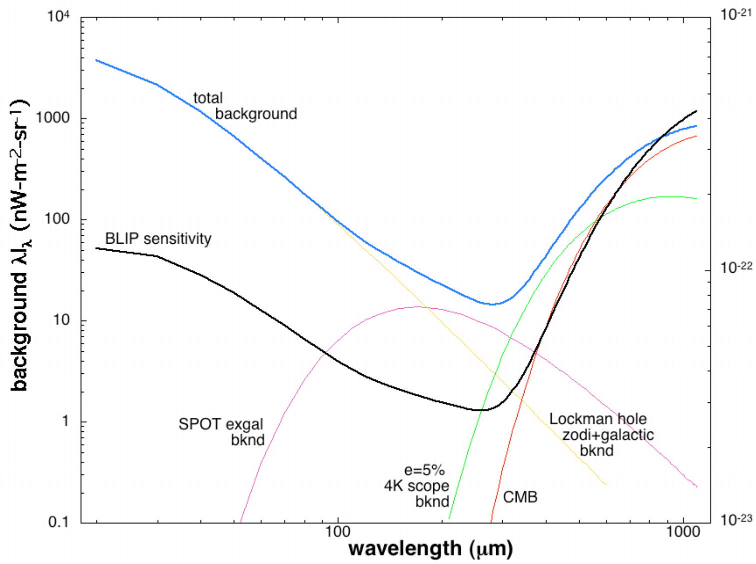

Figure II-1: The background radiation sources for SAFIR in the Lockman hole, which minimizes the galactic background emission. Cosmic background sources are shown superimposed on a telescope background scaled to e=0.05 at 4K.

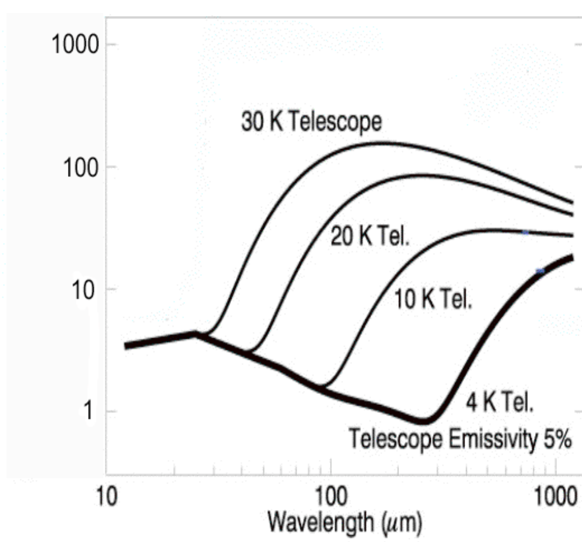

Figure II-2: The temperature dependence of the telescope thermal background is shown as a function of wavelength. The bold black line corresponds to a low-zodi (ecliptic pole) natural background limited sensitivity similar to the blue line in Figure II-1. This plot illustrates that telescope temperature is a strong capability driver for SAFIR.

Figure II-3 below shows how the cosmic background-limited sensitivities at R=1000 for the notional SAFIR compare with other far infrared spectroscopy platforms both in use and in development. This figure is excerpted from Appendix B which provides details on SAFIR sensitivity calculations. In order to achieve background limited performance, we assume a detector sensitivity of ~10^{-21} W-Hz$^{1/2}$, which is a factor of ten better than that achievable now. We believe that higher sensitivity is realizable with appropriate technology investment, and this is discussed in Section XV. With such optimal detectors, SAFIR would be 3-4 orders of magnitude more sensitive than other infrared observatories, with comparable sensitivity to ALMA for point source spectroscopy at the longest wavelengths. (Even with current detectors, SAFIR would still vastly outperform other observatories.) The rough consistency of spectral line sensitivity of SAFIR in the mid- and far-infrared with ALMA and other ground-based assets (JCMT and LMT) at millimeter wavelengths, and (just off the left edge of Figure II-3) with JWST at shorter wavelengths, makes SAFIR an ideal spectroscopic complement to these two observatories, which represent major national investments.

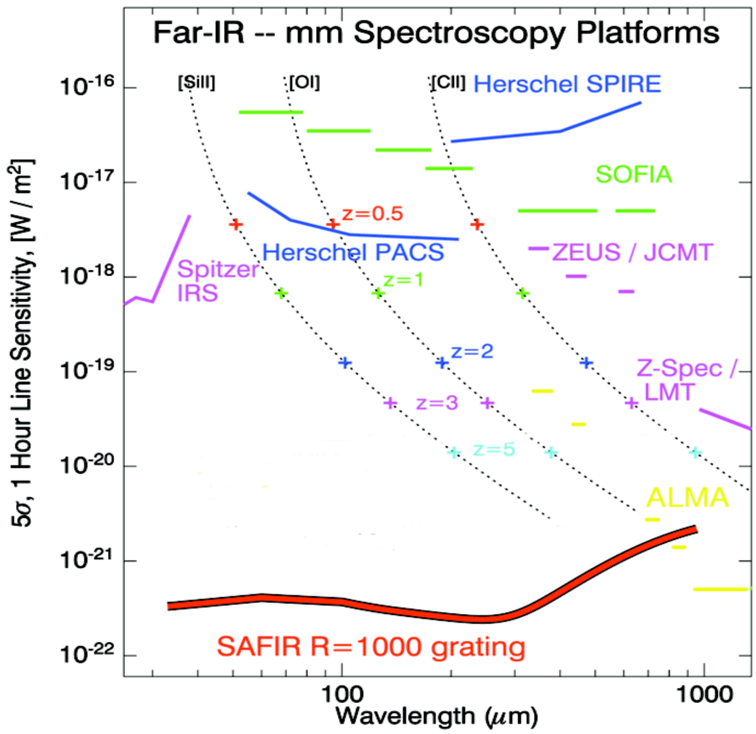

Figure II-3: Sensitivity of far-IR spectroscopy platforms now in operation or construction, including SAFIR, as excerpted from Appendix B. The SAFIR curve is calculated based on photon noise from the backgrounds, assuming a 10 m telescope with 75% aperture efficiency and 25% total instrument transmission in a single polarization, a factor of two degradation for chopping. As a guide to the science capability, overplotted are spectral line intensities from a $10^{12}L_o$ ULIRG at various redshifts assuming a fractional line intensity of 10^{-3} and the current cosmological model (Ω_{vac}= 0.73, Ω_{mat} = 0.27, H_0= 71).

At lower spectral resolution, such as for broad-band imaging applications, the background continuum puts significant power on the detectors, and dominates the noise. In this limit the detailed spatial structure of the background becomes much more important in understanding sensitivity limits. For CMB and zodiacal emission, the background is relatively smooth on these spatial scales, but the extragalactic background, which is dominated by distant galaxies, is not. This is highly relevant to SAFIR which, with spatial resolution of several arcseconds at the peak emission of galaxies, becomes strongly confusion limited with its high sensitivity. As discussed above, such confusion limits are strongly mitigated by increasing spatial resolution which is, for imaging, a driver for interferometry. Figure II-4 illustrates this.

The confusion limits lead to a modified sensitivity plot for SAFIR in broadband, and this is shown in Figure II-5. This figure shows how while at wavelength less then 100 μm, the sensitivity of SAFIR for broadband imaging is limited by the smooth zodiacal background, at longer wavelengths it is limited by confusion from extragalactic sources, and the point source sensitivity from large interferometers with much higher spatial resolution is much higher. These factors help bound the science goals of the mission.

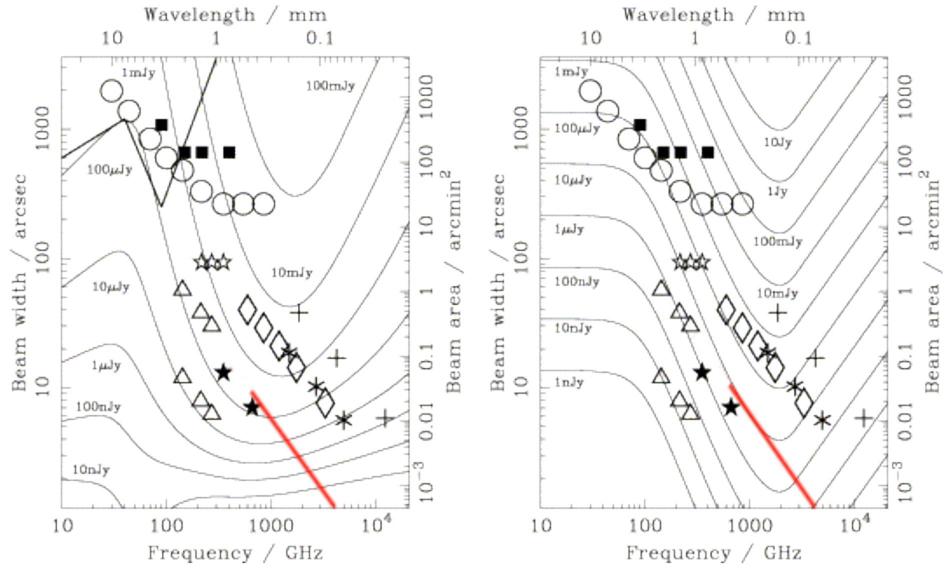

Fig. II-4: An approximate measure of the 1s confusion noise as a function of both observing frequency and angular scale through the infrared (Blain et al., 2002 Physics Reports, 369, 111). Contributions from extragalactic and Galactic sources are shown in the left and right panels, respectively. The bands and beamsizes of existing and future experiments are shown, including : diamonds—Herschel; crosses—Spitzer. With beamsizes of order 1-10", SAFIR is the bold red line in the lower right corner of these plots. Confusion from extragalactic sources is expected to generally dominate over that from the Milky Way ISM.

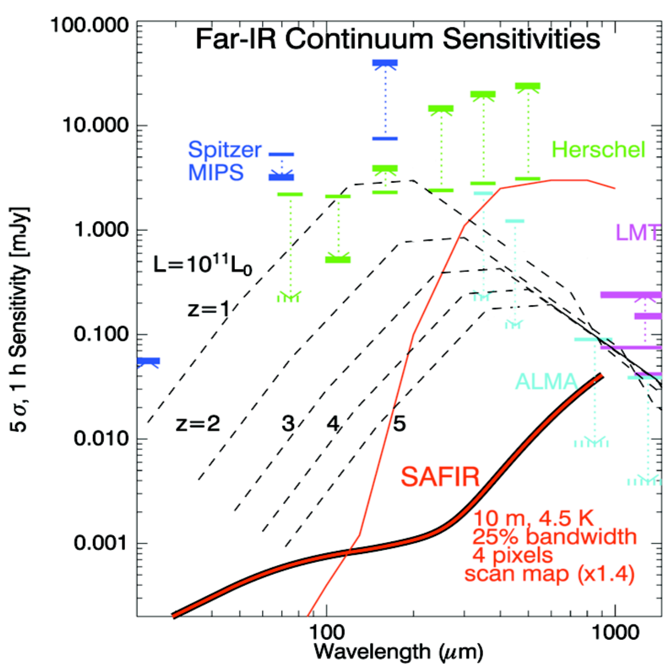

Figure II-5: Sensitivity to point sources in the continuum for SAFIR is compared to other far-IR platforms. This figure is extracted from Appendix B. Calculations for SAFIR assume aperture efficiency of 75%, a 50% throughput camera, and 4 diffraction-limited pixels coupling both polarizations are used to extract the source flux. The heavy red line is the SAFIR sensitivity set by the smooth CMB and zodi background, and can be considered the raw sensitivity in between extragalactic sources. The thin red line is the sensitivity limit from extragalactic confusion. Confusion limits are taken to be 10x the flux density at which there is one source/beam according to Blain et al. (see above). Upward arrows imply a platform which is confusion limited in <1 hr. Overplotted for reference (dashed black curves) are redshifted dusty galaxy SEDs appropriate for a 10^{11} L_0 galaxy.